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On the Nature of the Occurrence of Intermediate and Deep Earthquakes

2. Spatial and Temporal Clustering

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Abstract

Spatial and temporal clustering of intermediate and deep earthquakes have been studied from data of the location, depth, origin time and magnitude of earthquakes deeper than 100 km.

Multiplets frequently occur in the intermediate zone of the South Sandwich Islands, Colombia, the West Indies, the Aleutian Islands, Celebes Island, the Banda Sea, New Hebrides and the Hindu-Kush regions and in the deep zones of South America, Java-Banda Sea, Santa Cruz and the Fiji Islands region. These regions are characterized by the bending or the contortion of the descending lithosphere. In contrast, they are scarcely found in Central America, the Kuril Islands, Japan, Mariana or the Ryukyu Islands.

Hypocenters of shocks of each multiplet distribute on a long and slender plane in space. The largest shock in a multiplet is located at the extremity of the plane in almost all cases. Moreover, the shocks of each multiplet which occur in an area show the characteristic directional distribution. These distributions are strongly related to the distribution of the directions of the principal axes of stresses in the concerned regions.

On the analogy of the mechanism of the aftershock occurrence of shallow earthquakes, these characteristics of multiplets mean that small shocks of a multiplet are generated by the local concentration of the stress energy which is produced by the occurrence of a main fault plane of the largest shock.

From the time sequence of each multiplet it is found that there are some cases in which the largest shock occurs at the beginning of the series, that is, the aftershock type, but in many cases the multiplet type sequences are found. In cases of large shallow earthquakes a clear pattern of a main shock-aftershock sequence is generally found. This difference between the time sequence of shallow earthquakes and intermediate and deep earthquakes seems to be the reflection of the different physical conditions between the shallow zones and the deeper zones.

1. Introduction

The purpose of this study is to clarify the properties of the clustering of the intermediate and deep earthquakes by selecting numerous sets of earthquakes in which shocks occurred concentrating in time and space from the data of earthquakes deeper than a hundred kilometers.

The statistic character of time and space distributions of shallow earthquakes have been investigated in detail for a long time. For example, discussing based on laboratory experiments of the brittle fracture of materials, Mogi (1967) pointed out that the occurrence of fore-shocks, after-shocks and earthquake swarms is related to the heterogeneous structure of the crust.[1] Spatial and temporal distribution of after-shocks and earthquake swarms are being investigated in detail by Utsu (1969, 1970).[2,3,4]

The relations between the temporal variation of the mechanism and the activity in earthquake swarms were studied by Oike (1970).[5] Detailed descriptions on the characteristics of fore-shocks, after-shocks and earthquake swarms have been presented by Yamakawa (1966-1968).[6~10] Mogi (1968) indicated that after-shock areas of great earthquakes developed with time.[11] The question here is whether the various characteristics of the activity of shallow earthquakes described in these papers can be seen similarly in intermediate and deep earthquakes or not.

Mogi (1963)[12] and Utsu (1969)[13] indicated that the phenomena of the concentration of the occurrence in time and space were also found in intermediate and deep earthquakes. Isacks et al. (1967) investigated the spatial and temporal clustering of earthquakes in the Fiji-Tonga-Kermadec region.[14] A cluster of a small number of events closely related in space and time were termed a multiplet in their paper and some examples of deep multiplets were examined in detail. Santô (1969, 1970) pointed out that multiple events were found out also in the intermediate and deep zones of the seismically active regions.[15~18] Models for multiplets were proposed by Utsu (1970).[19]

Some data on multiplets with especially short time intervals (several seconds) have been studied. Analyzing the data of a deep earthquake in the Banda Sea region, origin time difference of 4.8 seconds and distance of 22 kilometers between hypocenters of two shocks which occurred successively were obtained by Oike (1969).[20] He discovered that the hypocenter of the second shock was situated on a nodal plane of the P waves radiated from the first shock. Fukao (1971) analyzed similarly a deep multiplet in west Brazil, and used the results to distinguish a slip plane of the main shock.[21]

In discussing the focal process of intermediate and deep earthquakes compared with that of shallow earthquakes, data on the clustering or multiplets are very important. In this study the properties of the occurrence of intermediate and deep earthquakes are mainly discussed from the reported data of location, depth, origin time and magnitude. And the general characteristics of multiplets are described by analyzing numerous examples.

2. Data

Two sets of data have been used in this study. One is a listing of earthquakes taken from the Bulletins of the International Seismological Center, 1964 and 1965, the other is a listing from the Priliminaly Determination of Epicenters of U.S. Coast and Geodetic Survey from 1966 to 1969. Origin times, depths, locations and magnitudes of all earthquakes whose foci were determined to be deeper than 100 kilometers have been adopted. Spatial and temporal distributions have been analyzed statistically on fifteen regions classified according to Oike (1971).[22] The total number of earthquakes in each region is shown in Table 1.

Data adopted do not distribute homogeneously in quality throughout the world. For example, in the South Sandwich Islands region, small shocks are scarcely listed

Table 1. Number of intermediate and deep earthquakes in each region.

No.	Region	Magnitude					Total Number
		3.0～3.9	4.0～4.9	5.0～5.9	6.0～6.9	undetermined	
1	South Sandwich Is.	0	12	38	1	0	51
2	Chile	19	114	14	1	6	154
3	Colombia-Peru-Bolivia	183	868	133	5	56	1,245
4	Dominica-Trinidad Tobago	4	36	5	1	10	56
5	Central America	59	145	23	1	0	228
6	Alaska-Aleutian	45	113	12	0	236	406
7	Kuril-Japan	17	183	58	2	18	278
8	Japan-Izu-Marianas	49	362	68	3	87	569
9	Ryukyu-Philippines	1	128	186	2	46	363
10	Indonesia	1	101	200	12	55	369
11	Solomon-New-Hebrides	31	413	206	10	193	853
12	Fiji-Tonga-Kermadec	155	1,127	234	4	80	1,600
13	New Zealand	0	7	10	1	132	150
14	Afghanistan	1	138	52	3	61	255
15	Italy-Greece-Turkey	1	52	7	0	11	71
	Total Number	566	3,799	1,246	46	991	6,648

because of the lack of near stations, but in and near Japan small shocks are frequently observed and reported. In the South American region, observation points distribute in a biased direction. In the first set of data described above many earthquakes in the New Zealand region are listed but in the second set they are scarcely listed. The results of statistical surveys of earthquakes in this region were reported by Vere-Jones et al. (1964, 1966).[23,24]

Distribution of the observation stations seen from a region is also related to the accuracy of the determination of hypocenters in this region. Of cause, it is essential to determine the relative possitions of shocks of a multiplet computing from the distribution of differences of travel times for each shock. In this paper however, assuming that the accuracy for the determination of the relative possitions of hypocenters in a multiplet is sufficient for the present purposes, reported data are used without any corrections.

3. Frequency Distribution of Time and Space Intervals

As used by Isacks et al. (1967)[25] the term"clustering refers to a concentration of earthquakes in time that also coincides with a concentration of earthquakes in space. To see these characteristics of clustering, two kinds of frequency distributions have been computed for each region.

The frequency distribution of the minimum time intervals is made for each region in the following way. A time interval, $T_i(\min)=t_j-t_i$, between an earthquake (E_i) and the first earthquake (E_j) that occurs subsequently to E_i within a sphere with the

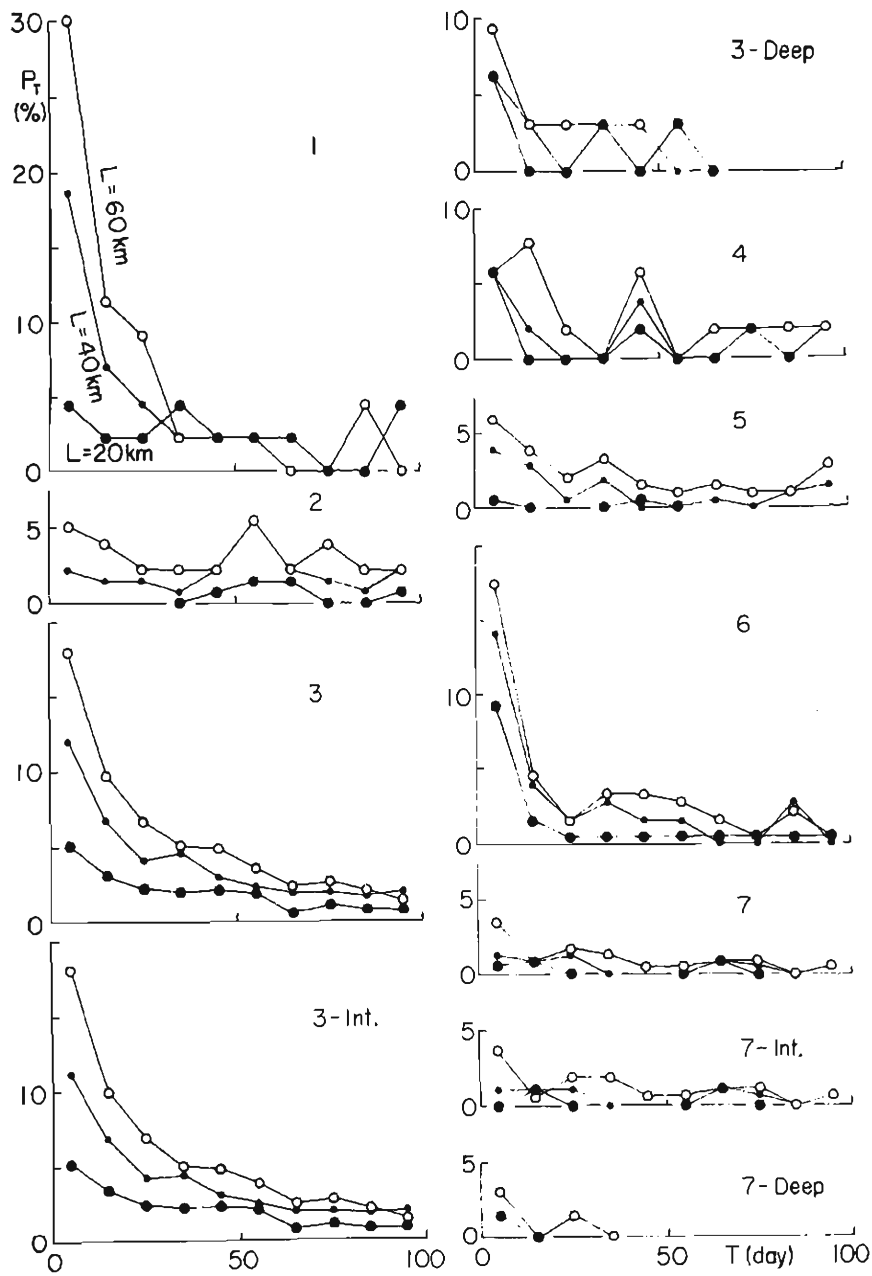

Fig. 1a. Frequency distribution of the shortest time intervals between each earthquake and the subsequent earthquakes within the limit of distances, L (km).

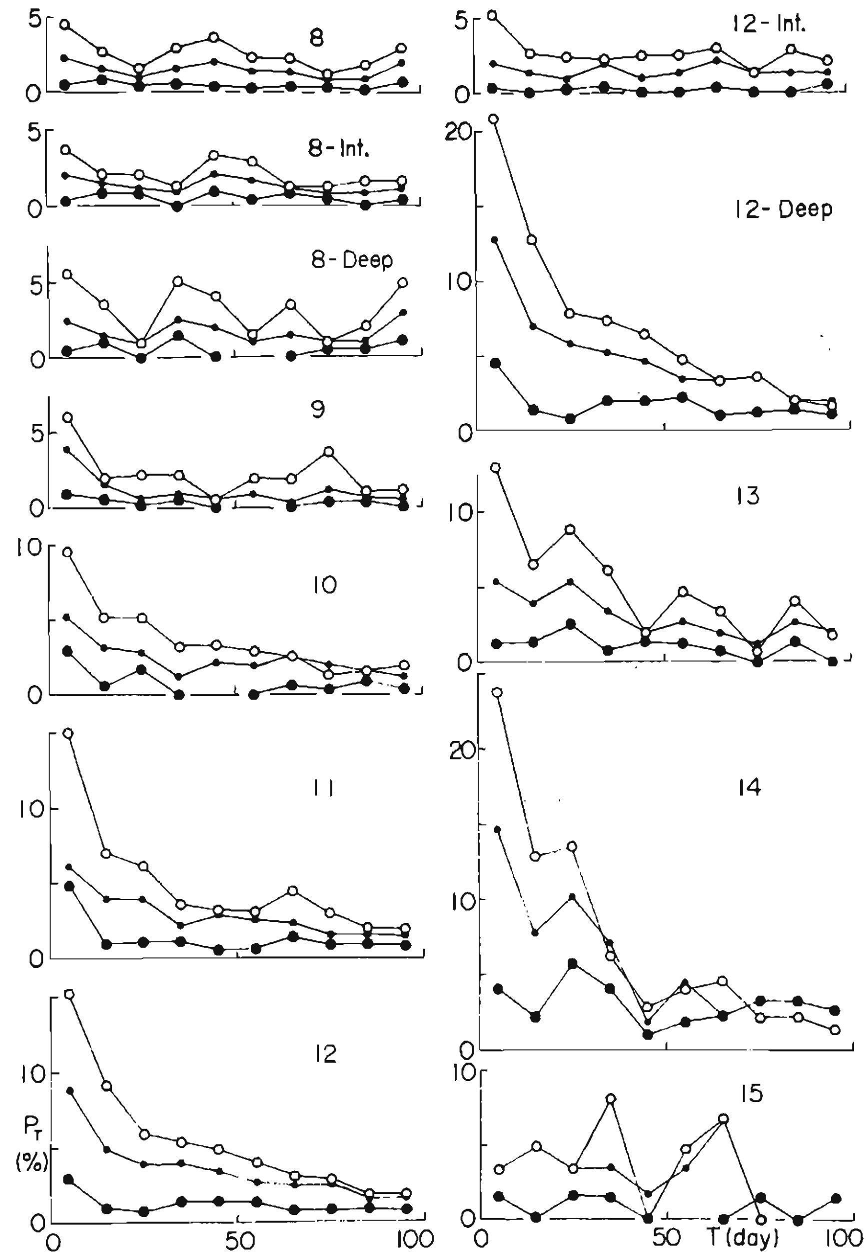

Fig. 1b. The frequency P_T indicate the percentage to the total number of earthquakes in the region. Regional numbers from 1 to 15 correspond to those in Table 1.

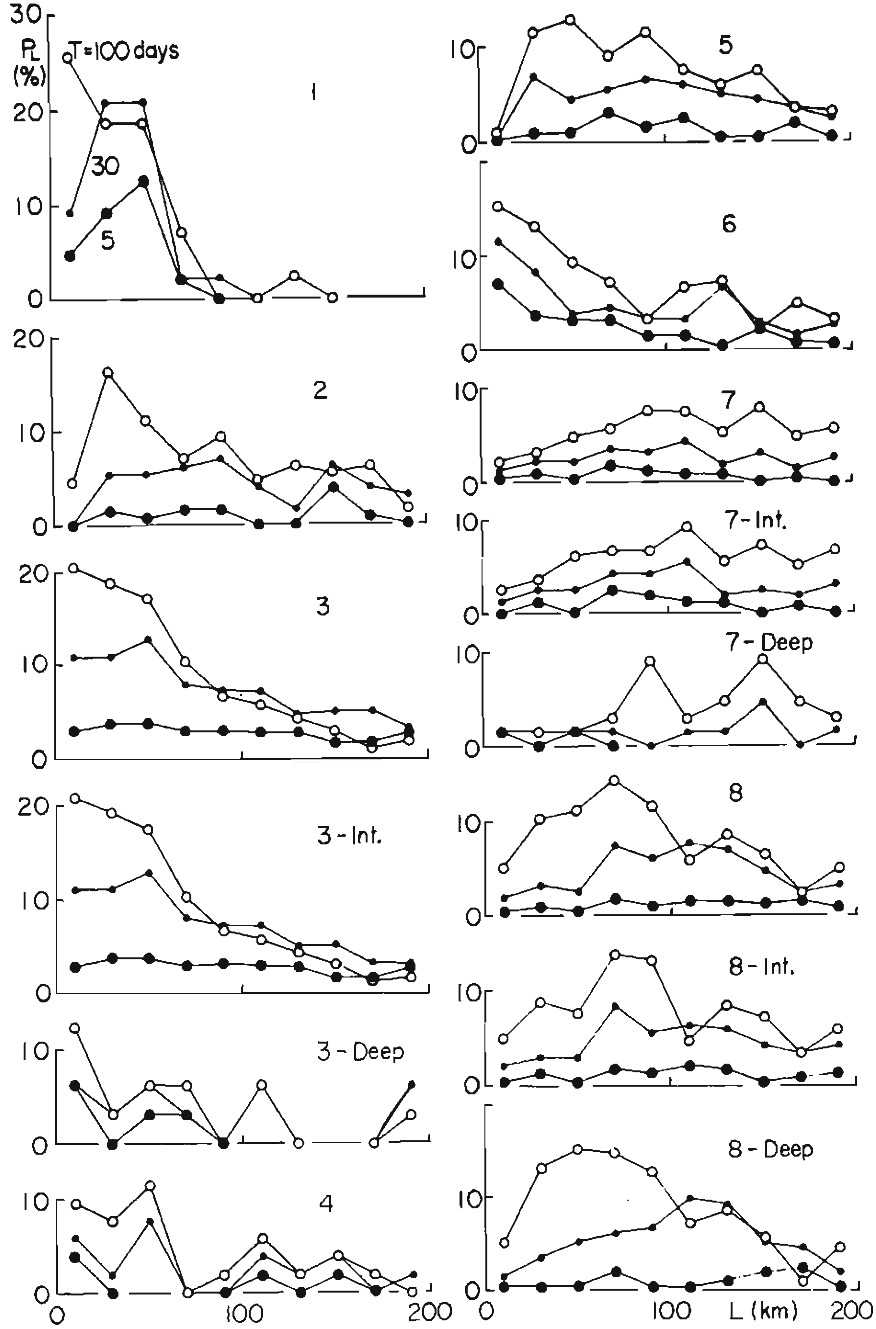
30
P_L (%)
T=100 days
20
30
10
5
0
1
20
2
3
3-Int.
3-Deep
4
0
100
200
10
5
6
7
7-Int.
7-Deep
8
8-Int.
8-Deep
L (km)

Fig. 2a.

radius of L (km), the center of which is the hypocenter of E_i is determined. Using the data for the years 1964 to 1969, T_i ($i=1, \ldots, n$) for all earthquakes of the region from 1964 to 1968 are obtained. The frequency distributions of T_i are shown in Fig. 1a,b for fifteen regions in the cases of $L=20$, 40 and 60 km. When L is sufficiently large, this distribution is similar to the frequency distribution of the differences in time between two successive earthquakes in a region.[26] The frequency is indicated by the

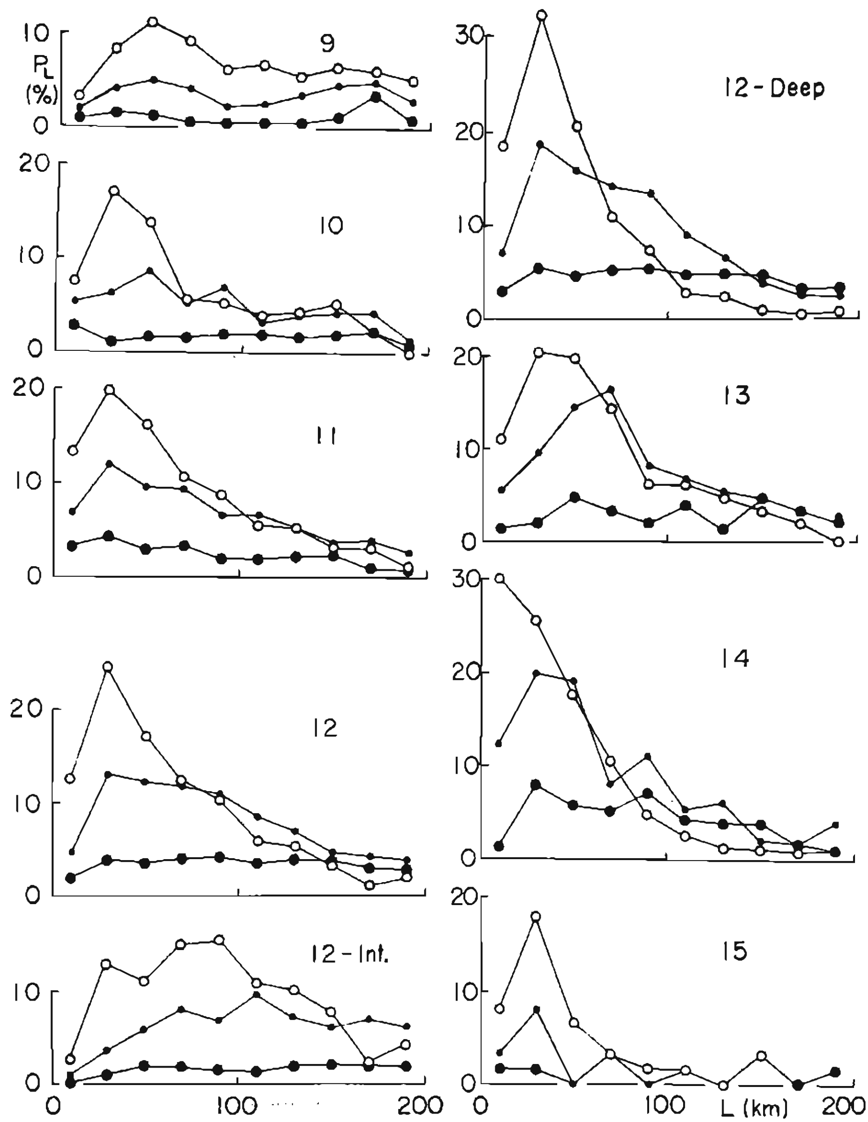

Fig. 2b. Frequency distribution of the shortest space intervals between each earthquake and the subsequent earthquakes within the limit of time interval, T (days).

percentage of the number of T_i for the total number of earthquakes (n) for the years 1964 to 1968 in the region as compared with the results of other regions. The high frequency at the small T and L corresponds to the clustering.

Using the same data, the frequency distribution of the shortest space intervals is made for each region by the following procedure. The nearest earthquale (E_j) that occurs after the occurrence of an earthquake (E_i) within a time interval T(days) from E_i is determined. The space interval (L_i) between the hypocenters of E_i and E_j is then calculated. $L_i (i=1, ..., n)$ for all earthquakes of the region for the years 1964 to 1968 are obtained. The frequency distributions of L_i are shown in Fig. 2a,b for fifteen regions in the cases of $T=5$, 30 and 100 days. The frequency is indicated by the percentage for the total number (n). The high frequency at the range of small T and L corresponds to the clustering similarly as in Fig. 1. When T is extended to be sufficiently large before and after the occurrence of E_i, this distribution corresponds to that obtained by Tomoda (1952)[27] and Utsu (1969).[28]

From the distributions shown in Figs. 1 and 2 it is concluded that there is a marked tendency to concentrate in time and space in the regions of the South Sandwich Islands, South America, the Aleutian Islands, southwest Pacific and the Hindu-Kush. But in and near Japan and in Central America the frequency distributions show scarcely such a tendency. In the Fiji-Tonga-Kermadec region the characteristics of the activity are quite different between the intermediate and deep zones.

In the regions where the character of the clustering is predominant, the shorter the time intervals (T) are, and a higher frequency is also observed, but the frequency distribution of the space intervals (L) has a peak at $L=20$ to 40 km, and shows a low frequency at the smaller L.

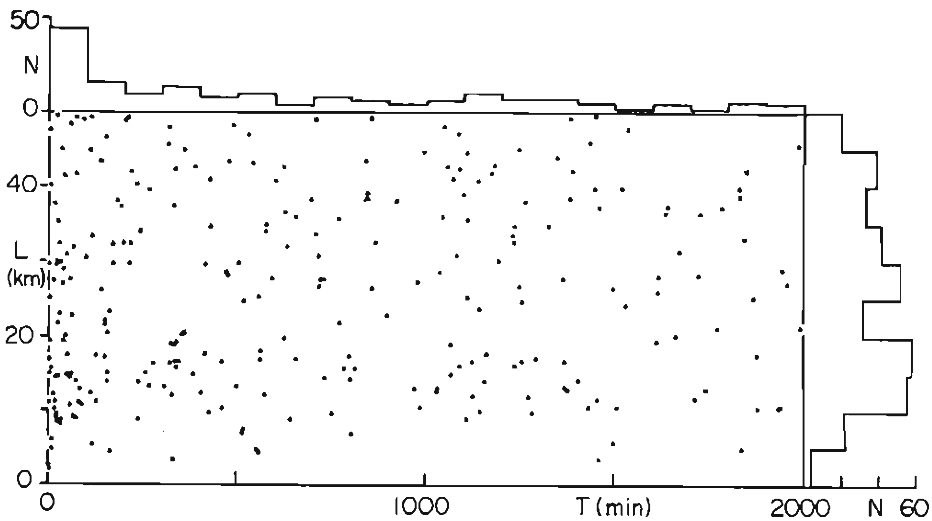

Fig. 3. Distribution of time and space intervals between each earthquake and subsequent earthquakes. The upper and the right-hand are the frequency distributions to the time and space intervals, respectively.

To observe this distribution in detail, time and space intervals from each earthquake to subsequent earthquakes are shown in Fig. 3. In this figure all shocks that occurred after an earthquake within the time interval of 2000 minutes and the space interval of 50 kilometers are plotted. The results indicate the similar properties to those mentioned above. Few earthquakes occur within a distance of 10 kilometers and a time interval of 2000 minutes from an earthquake. This means that the stress energy accumulated in the finite region around the focus is released by the occurrence of an earthquake.

4. Characteristics in Each Region

Results of the detailed analyses on the space and time distributions in regions where the frequency distributions in Figs. 1 and 2 show remarkable peaks at the small L and T are described. In such regions many multiplets can generally be found, and it seems that the high frequency at the short time and space intervals shown in Figs. 1 and 2 is due to the existence of many multiplets. These multiplets occur in the restricted smaller areas of these regions.

Some characteristics of individual multiplets and the relation between the distribusion of hypocenters in the region and the areas where multiplets frequently occur are shown region by region as follows.

a). South Sandwich Islands Region

The time sequence of the occurrence of intermediate earthquakes in this region is shown in Fig. 4. A tendency to concentrate in time can be observed.

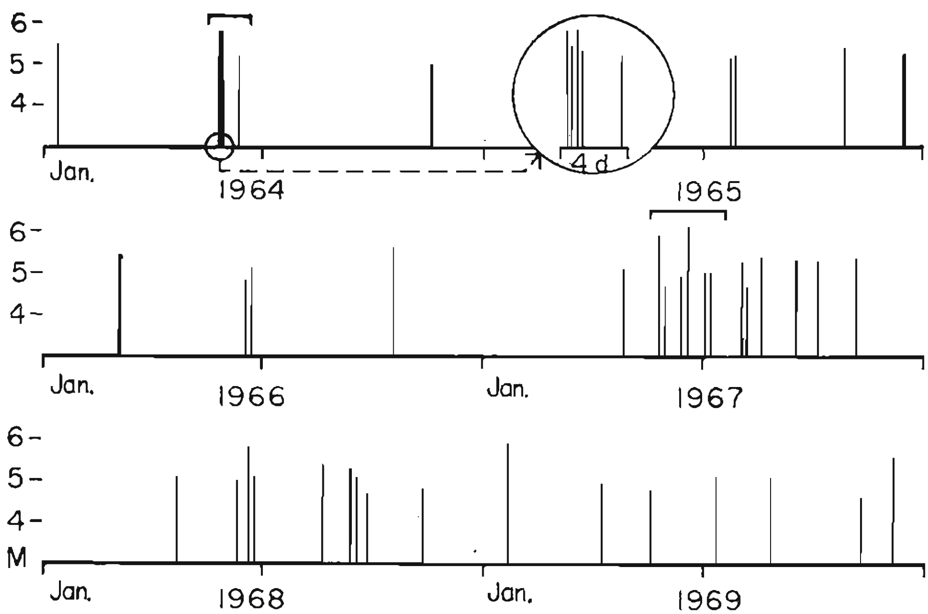

Fig. 4. Time sequence of the earthquakes in the South Sandwith Islands region whose depth are more than 100 kilometers.

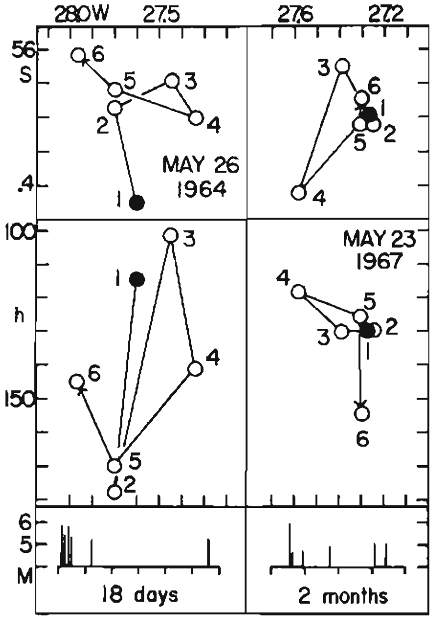

Fig. 5. Enlarged distribution of foci and time sequence of multiplets in South Sandwith Islands. The upper is the epicentral distribution, the middle is the vertical section and the loswer is the time sequence. M and h are the magnitude and depth in kilometers, respectively. Numbers indicate the order in time. Date is that of the first shock.

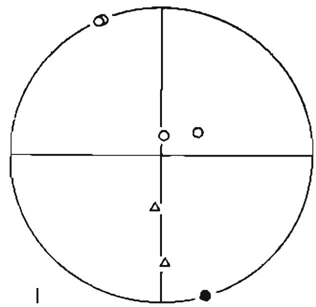

Fig. 6. Superposed distribution of directions of subsequent foci measured from the first shocks in the multiplets. Circles indicate the directions on the lower hemi-sphere projected by Wulff's net, and the triangles indicate their anti-podes on the upper hemi-sphere.
○ and △ ; $T \leq 10000$ min and $L \leq 30$ km,
● ; $T = 329$ min and $L = 3.5$ km.

Groups indicated by brackets in Fig. 4 are multiplets which also concentrate in space, distributions of hypocenters and time sequences are enlarged in Fig. 5. The focal process of the large earthquake of May 26, 1964 with many aftershocks is analyzed by Abe (1971).[29] The activity of these multiplets show the analogous pattern to that of shallow main shock and aftershocks. The largest shock occurs at the beginning of the time sequence and at the extremity of the directional distribution in space of aftershocks.

The distribution in a proper direction of hypocenters of multiplets are also found for doublets and triplets in this region. The directions of the subsequent earthquakes seen from the first shocks in multiplets are projected and superposed on a lower hemisphere shown in Fig. 6. For points of an upper hemi-sphere, their anti-podes are plotted by triangles. In such figures, as in other regions, solid circles and solid triangles indicate the remarkably short intervals of time and space.

The result indicates that the hypocenters of each multiplet in this region distribute in the direction along the vertical plane with strike of N 20° W.

b). South America Region

Distribution of the hypocenters of intermediate and deep earthquakes and those of multiplets are shown in Fig. 7 for the southern part of this region and in Fig. 8 for the northern part. Solid circles in Fig. 7 and Fig. 8 indicate the hypocenters of multiple shocks with short time intervals of several seconds analyzed by Chandra (1970)[30] and Fukao (1971),[31] respectively. There are four areas where numerous multiplets

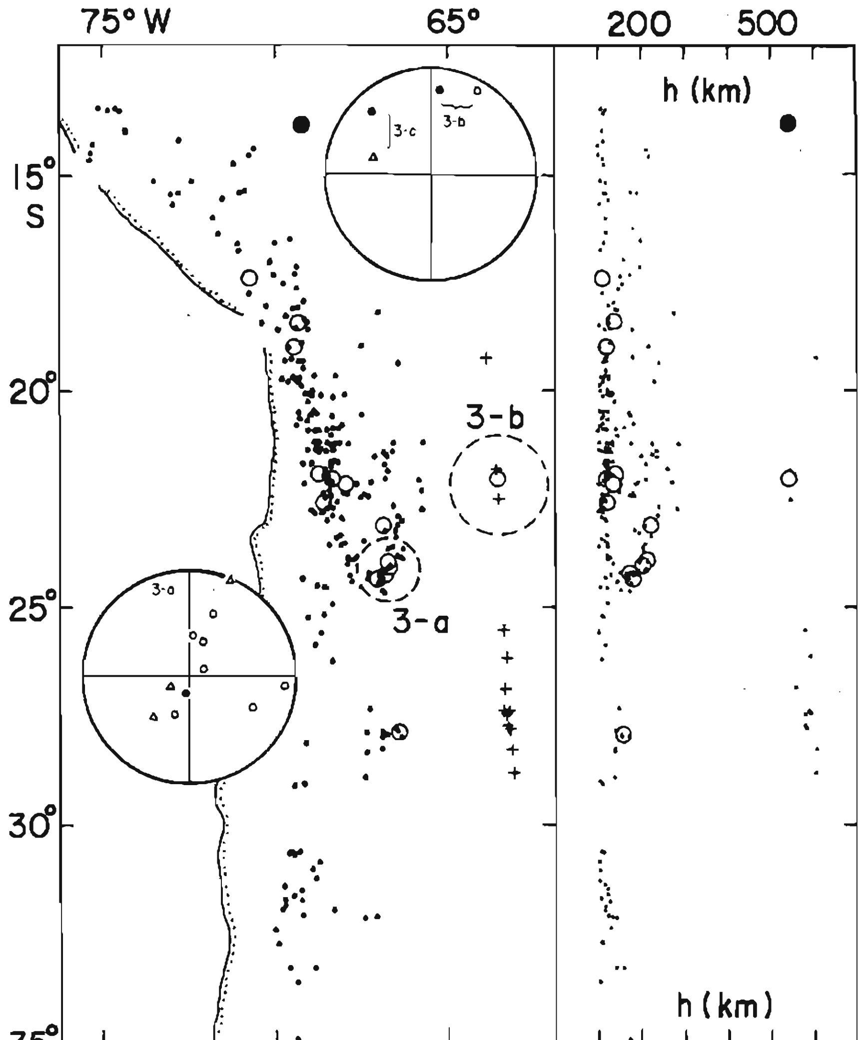

Fig. 7. Hypocenters of intermediate and deep earthquakes and multiplets in the Southwest part of South America are indicated as follows,

· ; $M \geq 4.5$ and h = 100-300 km,
+ ; $M \geq 4.5$ and h = 300-700 km,
○ ; Multiplets with the intervals of $T \leq 10000$ min and $L \leq 20$ km,
● ; The doublet analyzed by Chandra (1970).

In two large circles the directional distributions of subsequent foci are shown as follows,

○ and △ ; $T \leq 10000$ min and $L \leq 30$ km,
● and ▲ ; $T \leq 1000$ min and $L \leq 20$ km.

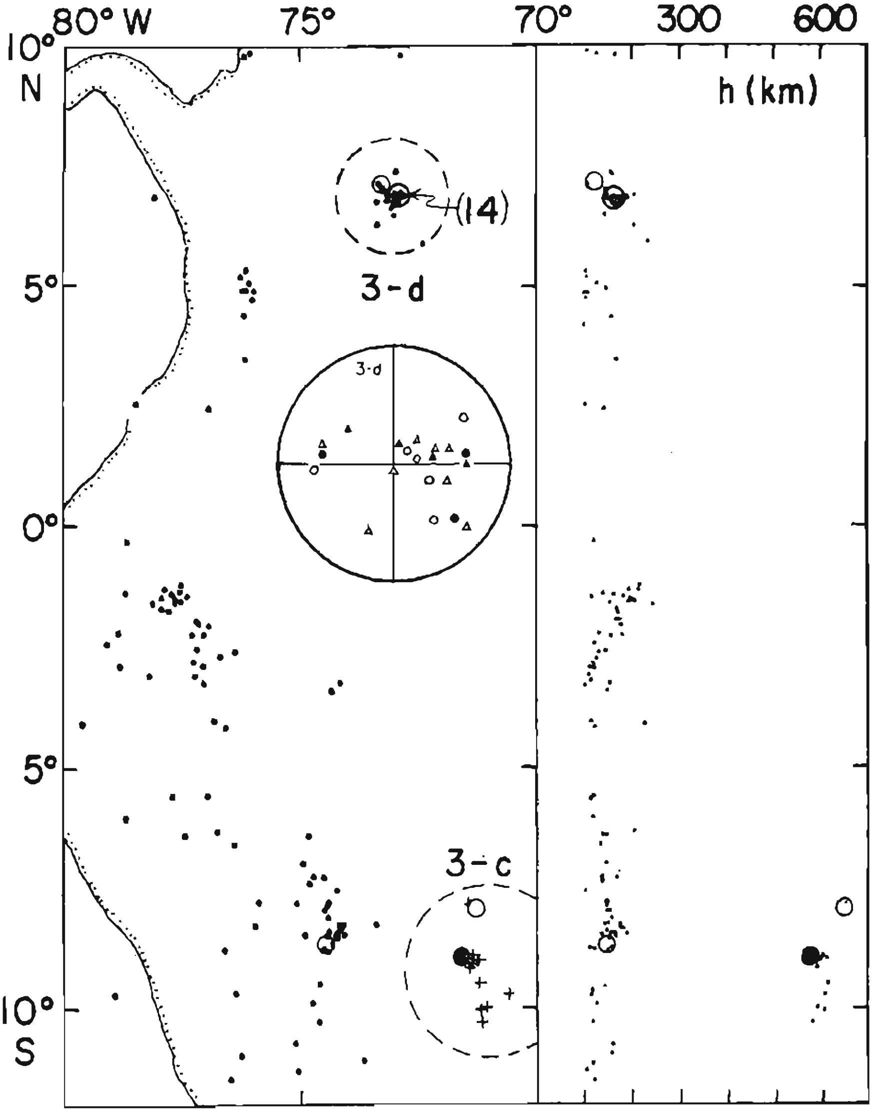

Fig. 8. Northwest part of South America. A solid circle in the map indicates the triplet analyzed by Fukao (1971). Open circles and open triangles in the directional distribution of the 3-d area indicate the intervals of $T \leq 5000$ min and $L \leq 20$ km. Other are similar to Fig. 7.

take place in comparison with the surrounding areas. They are the north-western part of Argentina (3-a), the Argentina-Bolivia border (3-b), the Peru-Brazil border (3-c) and the Colombia (3-d) regions. Multiplets occurring near a depth of 100 km are omitted here because they must be treated together with data for shallower earthquakes. (3-d) was called the nest N1 by Santô (1969) in his investigations of the characteristics of seismicity in South America,[32] multiplets occur most frequently in this region.

Distribution of the direction of hypocenters as seen from the first shocks in multiplets are also shown in Figs. 7 and 8. They distribute in a direction proper to each area. Distribution of hypocenters and the time sequence of the multiplets in and near the 3-a area are enlarged in Fig. 9. Hypocenters of the multiplet of 1969 distribute in a north-south direction, dipping toward the north in the early stages but changing to an east-west direction later. This implies the developement of a conjugate set of fault planes. The largest shock is situated at the end of the slender distribution in space. Another multiplet which occurred at a shallower area is also shown in Fig. 9. Also in this case the largest shock occurred at the extremity of the spatial distribution.

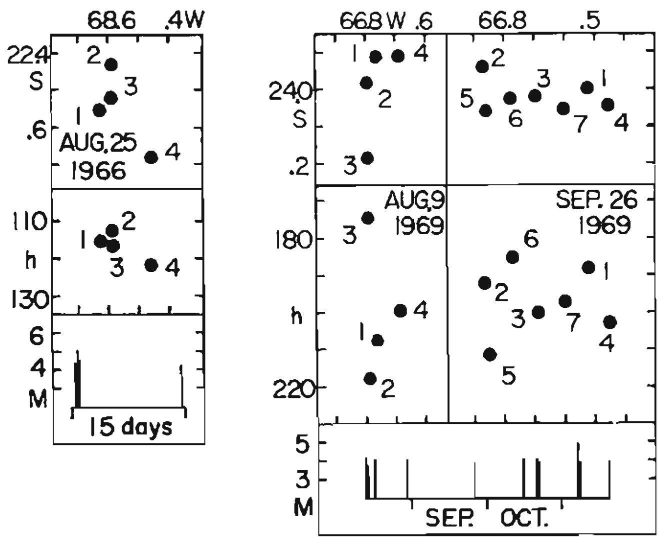

Fig. 9. Multiplets in 3-a area (right) and near 3-a area (left).

In the 3–d (Colombia) area, intermediate earthquakes occur frequently in a small range in space. The time sequence over six years in this area is shown in Fig. 10. Groups with brackets are multiplets which coincide with the concentration in space, and they are indicated in detail in Fig. 11.

Hypocenters of intermediate earthquakes in this area distribute in the NW–SE direction as indicated by Santô (1969)[32] and the axis of maximum pressure obtained by Oike (1971) lines in the same direction.[33] Hypocenters of shocks in each multiplet in Fig. 11 distribute nearly to the east-west, as is found in the directional distribution of subsequent earthquakes, with short intervals in time and space in Fig. 8. These are oblique at an angle of almost 45 degrees to the hypocentral distribution and the axis of maximum pressure.

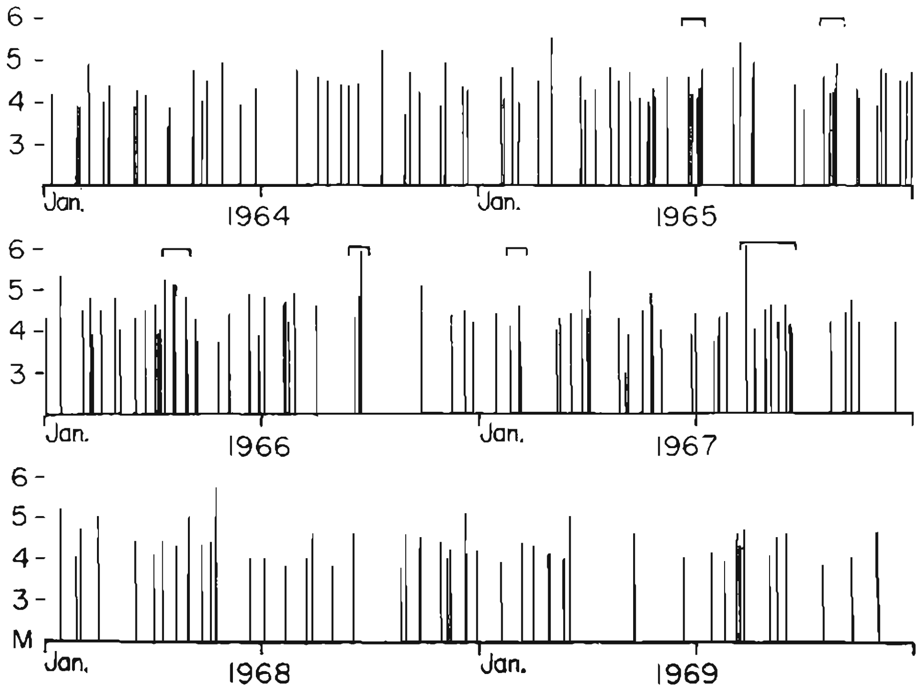

Fig. 10. Time sequence of 3-d (Colombia) area.

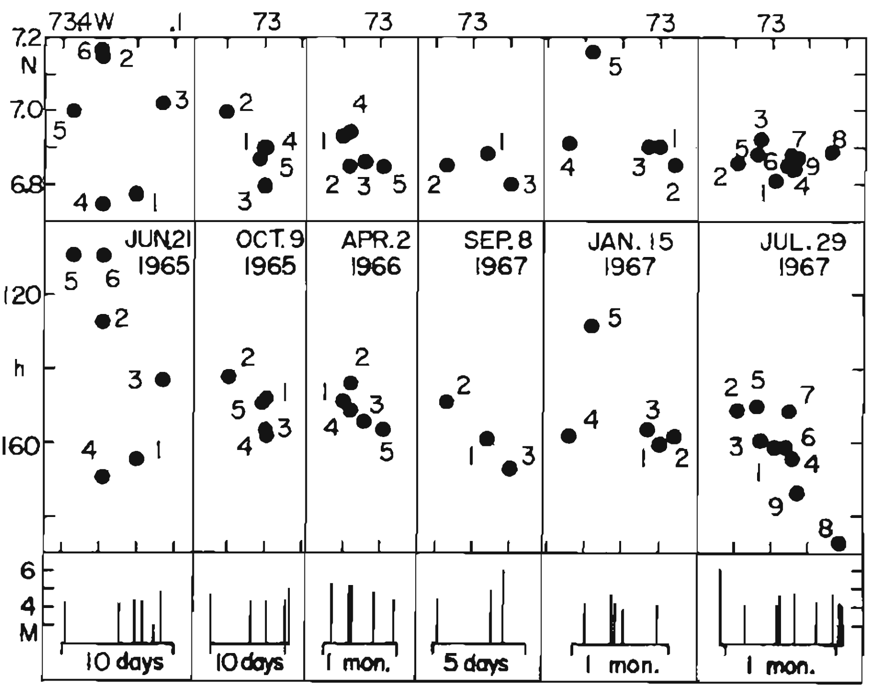

Fig. 11. Multiplets in Colombia (3-d).

The largest shock in each multiplet in Fig. 11 takes place at the end of the distribution of hypocenters in space, but it dose not always occur at the beginning of the time sequence.

c). West Indies Region

Hypocenters of intermediate earthquakes and multiplets are indicated in Fig. 12. Three doublets are found only at the southern extremity of this region. The directions of second shocks seen from the first distribute on the vertical plane with the strike almost north and south.

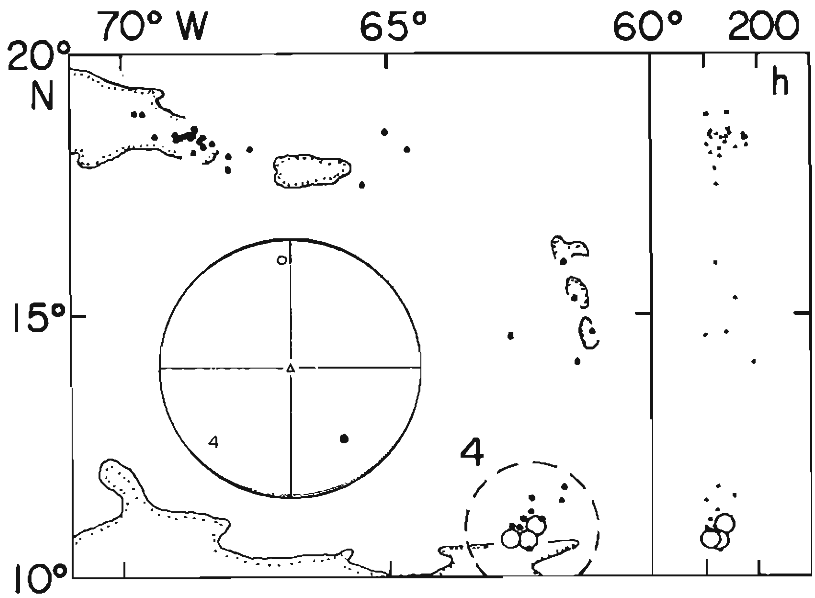

Fig. 12. West Indies region.
· ; $M \geq 4.0$,
○ ; Multiplets of $T \leq 10000$ min and $L \leq 30$ km.
In the directional distribution,
○ ; $T = 3424$ min and $L = 18.1$ km,
△ ; $T = 7234$ min and $L = 18.0$ km,
● ; $T \fallingdotseq 1$ min and $L = 2.7$ km.

d). Alaska and Aleutian Islands Region

Many multiplets are found in this region but they contain aftershocks of large shallow earthquakes. It is desirable therefor to take into consideration data on the shal lower earthquakes.

The distribution of directions of subsequent earthquakes with remarkably short time and space intervals are shown in Fig. 13. Triangles indicate the anti-podes, the result shows that subsequent earthquakes take place around the south-east side of the first shocks in this region.

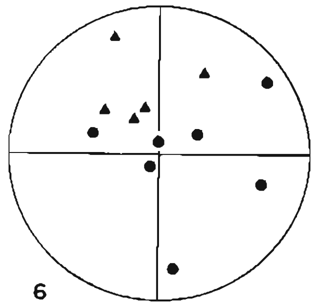

Fig. 13. Alaska and Aleutian region.
●, ▲ ; $T \leq 1000$ min and $L \leq 20$ km.

e). Izu-Mariana Islands Region

From Kuril-Japan to Izu-Marianas the tendency to concentrate in time and space is scarcely seen in Figs. 1 and 2. If compared, however in the deep zone of Izu-Marianas the concentration in time and space can be found. Multiplets in the Izu-Marianas region which have been distinguished under the milder conditions of time and space intervals than the other regions are shown in Fig. 14. Only a doublet belonging to 8–b area has short space and time intervals of $L=7.1$ km and $T=514$ min. The directional distribution is also shown in Fig. 14.

A few multiplets are found in the intermediate zone above 8–b area. Utsu (1969) investigated the time and space distribution of deep earthquakes in and near Japan and pointed out that directions of the second shocks seen from the first of pairs of earthquakes occurring within intervals of $L=150$ km and $T=30$ days are systematically perpendicular to the seismic belts.[34]

f). Philippines-Celebes Region

Multiplets are scarcely seen among intermediate and deep earthquakes in these regions. Excepting the multiplets near 100 km only at a depth of 200 km in the northeast of Celebes island are several multiplets found. Distribution of hypocenters and multiplets is shown in Fig. 15. The directional distribution of the subsequent shocks of each multiplet are superposed and shown in Fig. 15 under the mild conditions of $T \leq 30000$ min and $L \leq 30$ km. This gives the distribution in a proper direction.

g). Java-Banda Sea Region

Hypocenters of intermediate and deep earthquakes and multiplets are shown in Fig. 16. Comparatively speaking, numerous multiplets occur in these regions, concentrating in specific areas, namely in the deep zones of the Java Sea (10-a) and the Banda Sea (10–b) and the intermediate depth of the Banda Sea (10–c) regions. Similar properties were also obtained by Santô (1969).[35] A solid circle in 10–b area is a multiple shock with intervals of $T=4.8$ sec and $L=22$ km analyzed by Oike (1969).[36]

The distribution directions of hypocenters seen from the first shocks are shown in Fig. 17. They distribute distinctly on a vertical plane whose strike is parallel to the

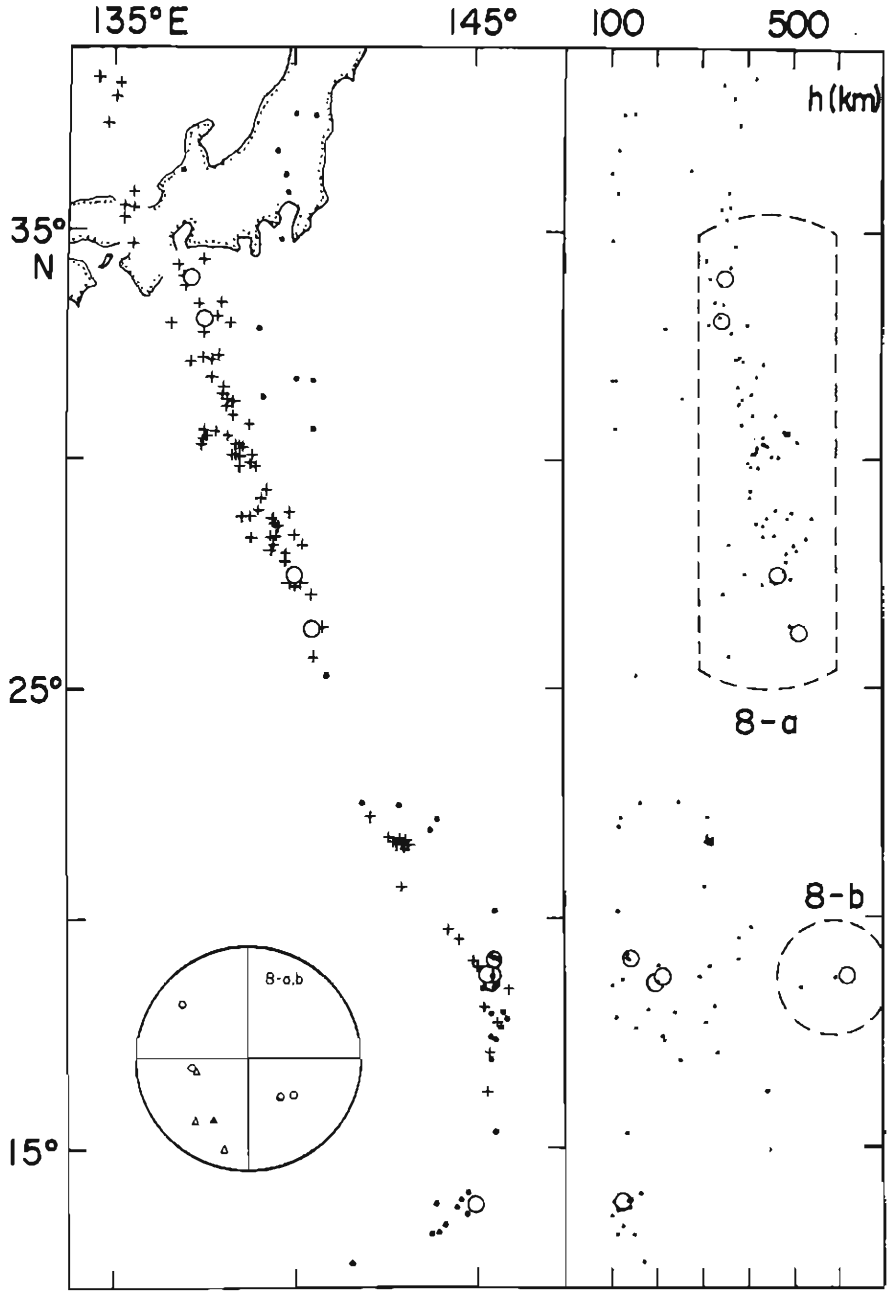

Fig. 14. Izu-Marianas region.
· ; $M \geq 5.0$ and h = 100-300 km,
+ ; $M \geq 4.5$ and h = 300-700 km,
○ ; Multiplets of $T \leq 10000$ min and $L \leq 30$ km.
In the directional distribution,
○ , △ ; $T \leq 15000$ min and $L \leq 40$ km,
● ; T = 514 min and L = 7.1 km.

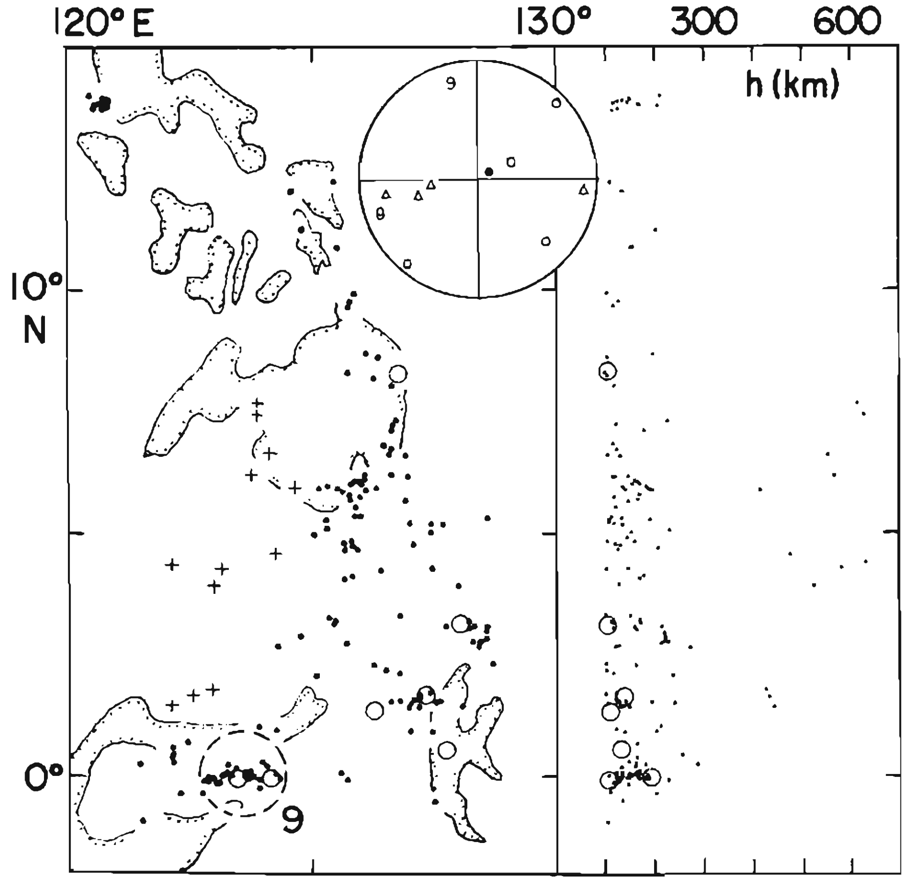

Fig. 15. Philippines-Celebes region.
· ; $M \geq 5.0$ and h = 100-300 km,
+ ; $M \geq 5.0$ and h = 300-700 km,
○ ; Multiplets of $T \leq 30000$ min and $L \leq 30$ km.
In the directional distribution,
○, △ ; $T \leq 30000$ min and $L \leq 30$ km,
● ; $T = 44$ min and $L = 17.5$ km.

seismic plane in each area and make an angle of about 30 degrees between 10–a and b areas and in 10–c.

h). New Guinea-Solomon Islands Region

Hypocenters of intermediate and deep earthquakes and multiplets are shown in Fig. 18. Multiplets are found around a depth of 200 km in the eastern part of New Guinea (11–a) and around a depth of 100 km in the Bougeinville Island, but those with short intervals simultaneously in time and space are rarely observed. In the directional distribution of subsequent hypocenters of multiplets (11–a) in Fig. 20, a solid circle indicates the shortest interval of $T = 7354$ min and $L = 5.4$ km.

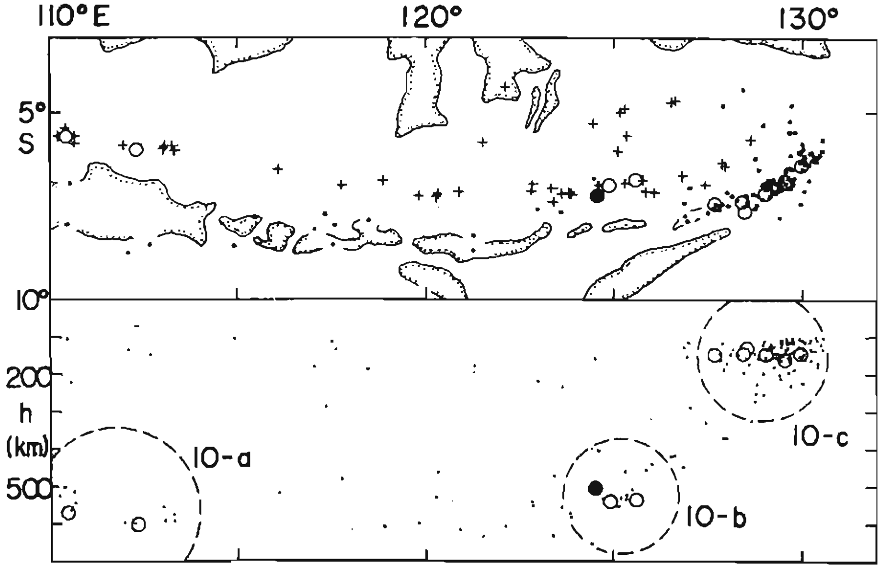

Fig. 16. Java-Banda Sea region.
· ; $M \geq 5.0$ and h = 100-300 km,
+ ; $M \geq 5.0$ and h = 300-700 km,
○ ; Multiplets of $T \leq 10000$ min and $L \leq 20$ km,
● ; The doublet analyzed by Oike (1969).

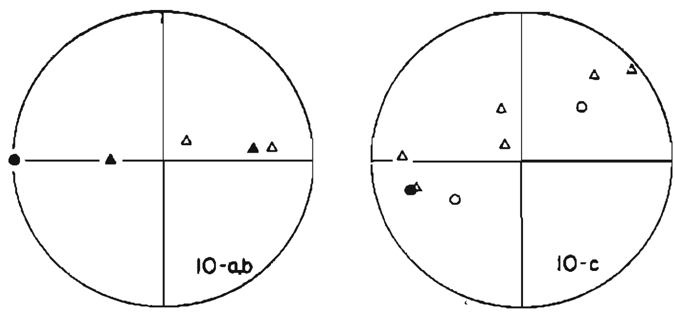

Fig. 17. The directional distributions of subsequent earthquakes in 10-a, b and c areas.
○, △ ; $T \leq 10000$ min and $L \leq 30$ km,
●, ▲ ; $T \leq 1000$ min and $L \leq 20$ km.

i). New Hebrides Islands Region

Hypocenters of intermediate and deep earthquakes and multiplets are shown in Fig. 19. There are three areas (11-b,c and d) where many multiplets are distinguished. In the deep zone of the Santa Cruz island the remarkable characteristic of concentrating in time and space has been observed.

The directional distributions of subsequent hypocenters of multiplets in these areas are shown in Fig. 20. In the 11-c area, only especially short intervals are plotted. These results indicate that the hypocenters of subsequent earthquakes in multiplets

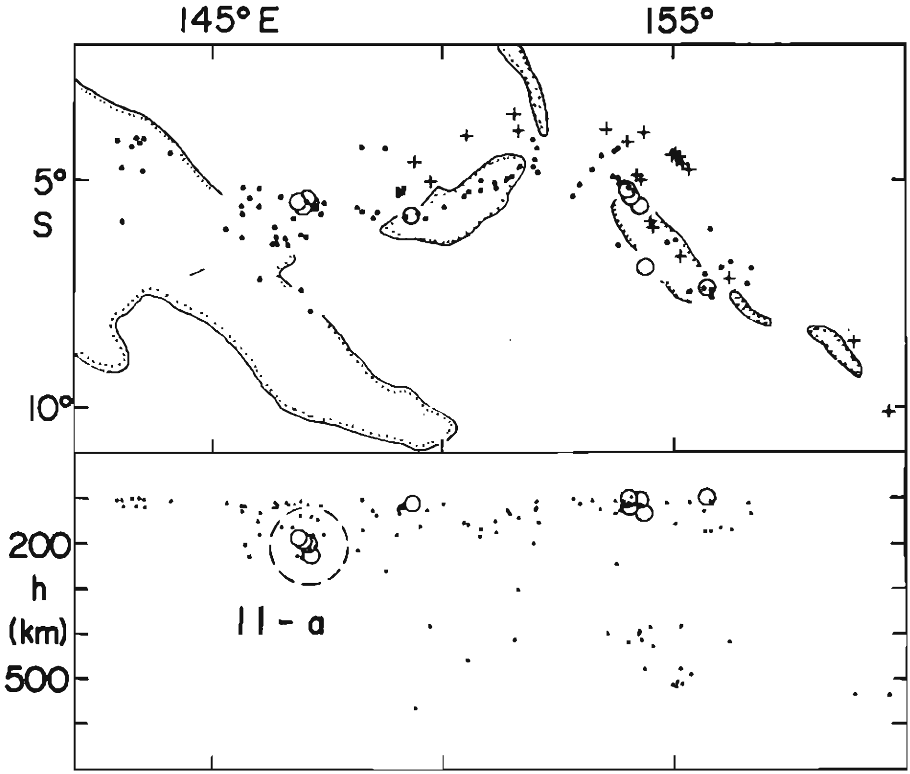

Fig. 18. New Guinea-Solomon Islands region.
· ; $M \geq 5.0$ and h = 100-300 km,
+ ; $M \geq 4.0$ and h = 300-700 km,
○ ; Multiplets of $T \leq 10000$ min and $L \leq 30$ km.

distribute in the direction parallel to a certain plane or in the biased direction of each area.

Multiplets that occurred in the shallower part around a depth of 100 km near 11–d are excluded from the plots in Fig. 19. Though an example is shown in Fig. 21. The direction of distribution of hypocenters coincides with the results of 11–d in Fig. 20. The seismicity in this region was investigated by Santô (1970) and the shallow clusterings were studied in detail.[37]

j). Fiji-Tonga-Kermadec Region

Hypocenters of intermediate and deep earthquakes and multiplets are shown in Fig. 22. In this region numerous multiplets occur among deep earthquakes but scarcely among intermediate ones. They are found most frequently around a depth of 500 km in the Fiji Islands region. Multiplets with especially short time and space intervals are shown in Fig. 22. The clustering in this region was investigated in detail by Isacks et al. (1967).[38] Data used in the present study overlap with theirs of the first two years and various characteristics obtained in this study coincide with their results.

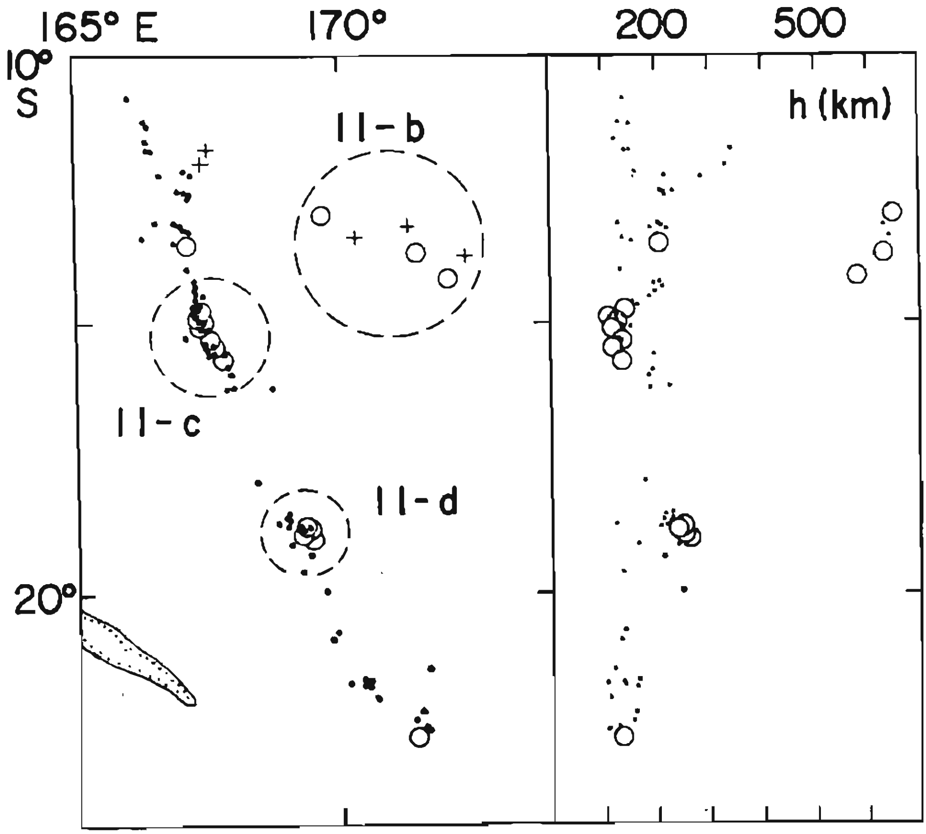

Fig. 19. New Hebrides region.
· ; $M \geq 5.0$ and h = 100-300 km,
+ ; $M \geq 5.0$ and h = 300-700 km,
o ; Multiplets with remarkably short time and space intervals or with intervals of $T \leq 10000$ min and $L \leq 30$ km ($h \geq 200$ km).

The distributions in time and space of shocks of multiplets with more than three shocks are enlarged and shown in Fig. 23. Multiplets of December 19 and 25, 1965 were analyzed by Isacks et al (1967)[38] and hypocenters of shocks for them are situated continuously in space. Hypocenters of two other multiplets also slenderly distribute in the same direction.

Deep earthquakes around the Fiji Islands seem to occur along two seismic active lines which run in the NW-SE direction, and almost all multiplets in this area are found among the southwestern group. The multiplet of November 24, 1969, is an example of those which occurred in the north-eastern group and it alone indicates the hypocentral distribution dipping toward the northwest direction.

A multiplet in the southern part, 12-b, is shown in Fig. 24. Both distribution of hypocenters and time sequence indicate the analogous pattern with the shallow main

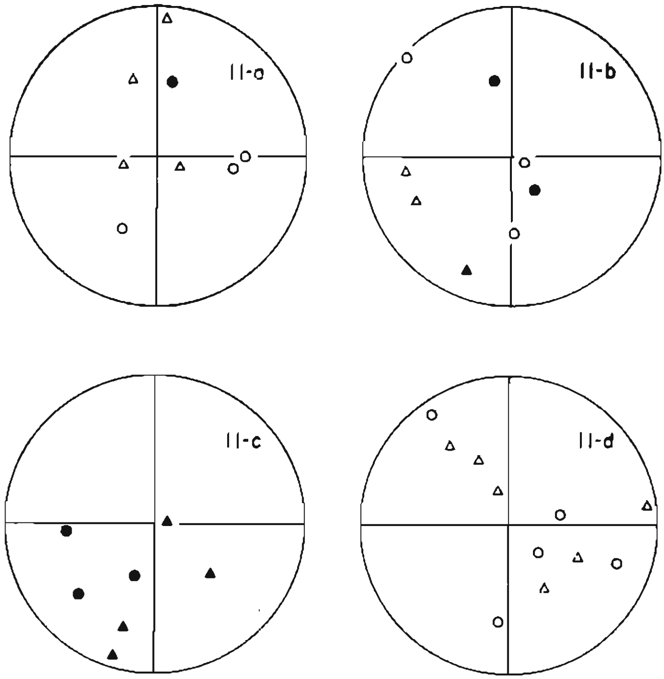

Fig. 20. The directional distribution of subsequent earthquakes.
○, △ ; $T \leq 20000$ min and $L \leq 40$ km (in 11-a and b),
$T \leq 10000$ min and $L \leq 30$ km (in 11-d),
●, ▲ ; $T = 7354$ min and $L = 5.4$ km (in 11-a),
$T \leq 1000$ min and $L \leq 20$ km (in 11-b and c).

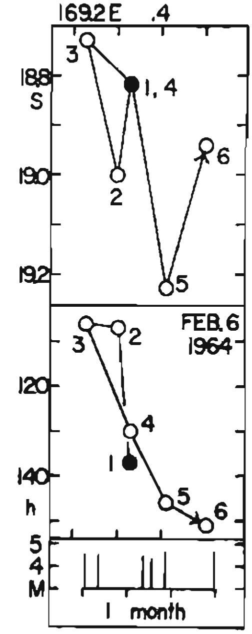

Fig. 21. A multiplet near the 11-d area.

shock-aftershocks sequence. The largest shock occurs at the end of the hypocentral distribution in space and at the beginning of the time sequence.

Directional distribution of hypocenters of subsequent earthquakes seen from the first shocks in multiplets are shown in Fig. 25. Though the strike of the seismic plane of 12-a is in a NW-SE direction, while that of 12-b is in a NE-SW, the results in Fig. 25 show that the subsequent hypocenters in these two areas distribute in the same direction. The principal axes of the earthquake generating stresses in these areas also distribute in the same direction with each other (Isacks et al., 1971 and Oike, 1971).[39,40]

k). Hindu-Kush Region

Characteristics of concentration in time and space are clearly observed in this region, Figs. 1 and 2. Hypocenters of intermediate earthquakes and multiplets are shown in Fig. 26. Frequency distribution of earthquakes with depth show a minimum of 180 km, Fig. 27. Almost all multiplets in this region are found in the deeper group, and their foci align themselves on a line about 100 km long near a depth of 200 km.

The time sequence of earthquakes which occurred in this region within a depth of 180 to 260 km and west of Long. 71.3° E is indicated in Fig. 28. The groups in

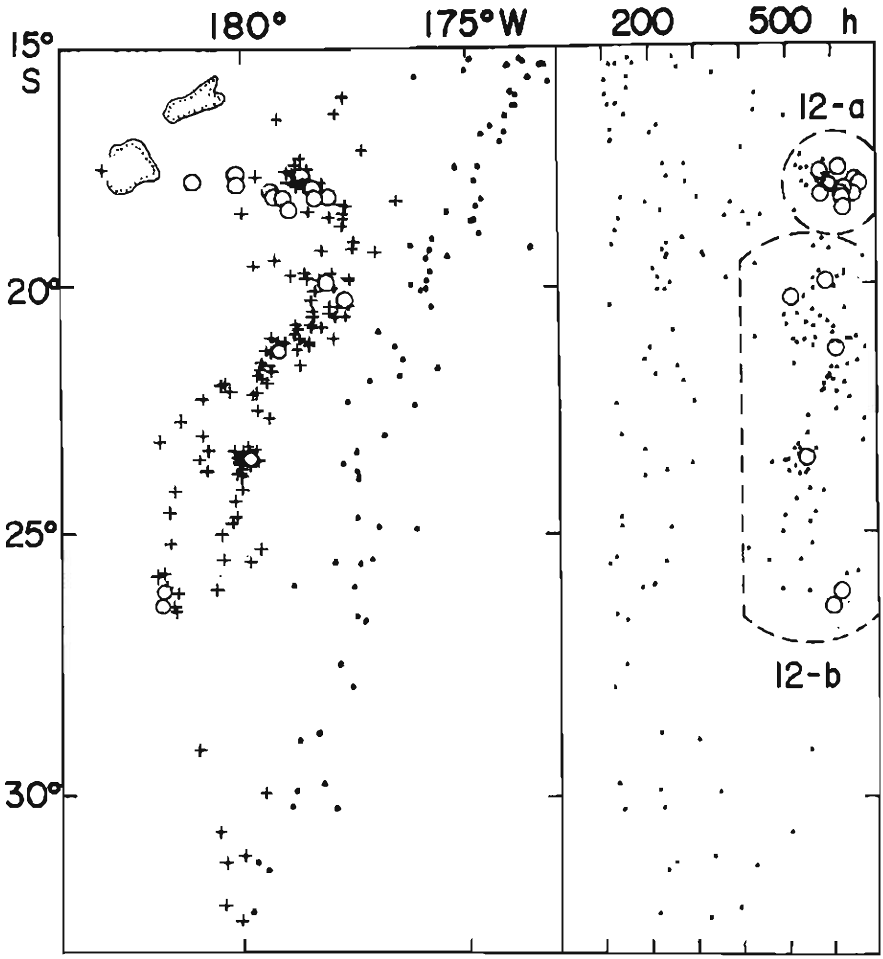

Fig. 22. Fiji-Tonga-Kermadec region.
· ; $M \geq 5.0$ and h = 100-400 km,
+ ; $M \geq 5.0$ and h = 400-700 km,
○ ; Multiplets of $T \leq 1000$ min and $L \leq 20$ km.

brackets are the multiplets which also concentrate in space and they are enlarged and shown in Fig. 29.

Hypocenters in each multiplet distribute in a long and slender range in space in an east-west direction, the largest shock is situated at the end of the distribution. The hypocenters of successive earthquakes distribute in the directions parallel to the vertical plane with the strike in an east-west direction as is indicated in Fig. 26, and this coincides with the distribution mentioned above. These characteristics indicate that the distribution of subsequent hypocenters does not spread in the direction where the axes of maximum pressure distribute (Oike, 1971).[40)]

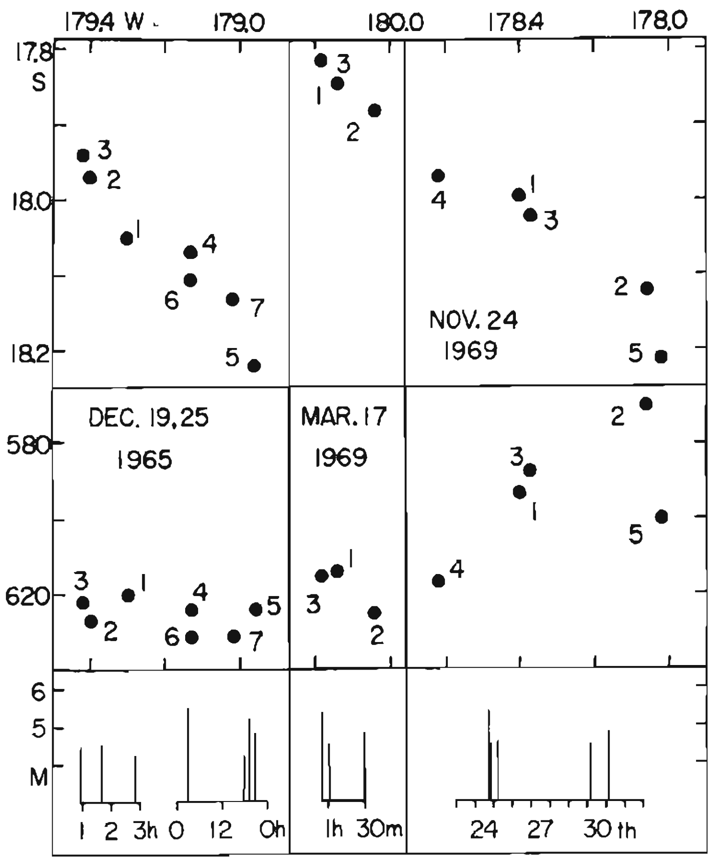

Fig. 23. Deep multiplets in Fiji Islands (12-a).

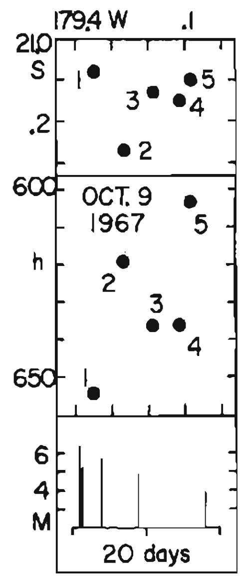

Fig. 24. A deep multiplet in Tonga.

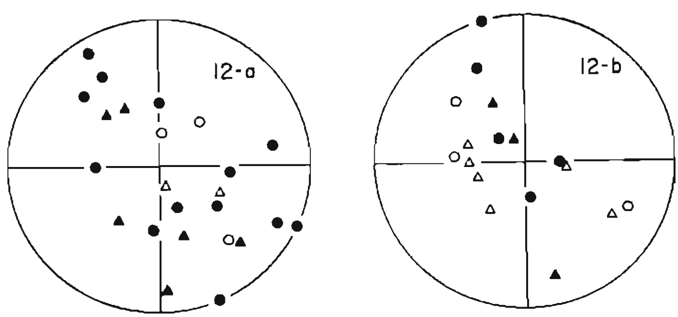

Fig. 25. Fiji (12-a) and Tonga-Kermadec (12-b) regions.
○, △ ; $T \leq 5000$ min and $L \leq 20$ km,
●, ▲ ; $T \leq 1000$ min and $L \leq 20$ km.

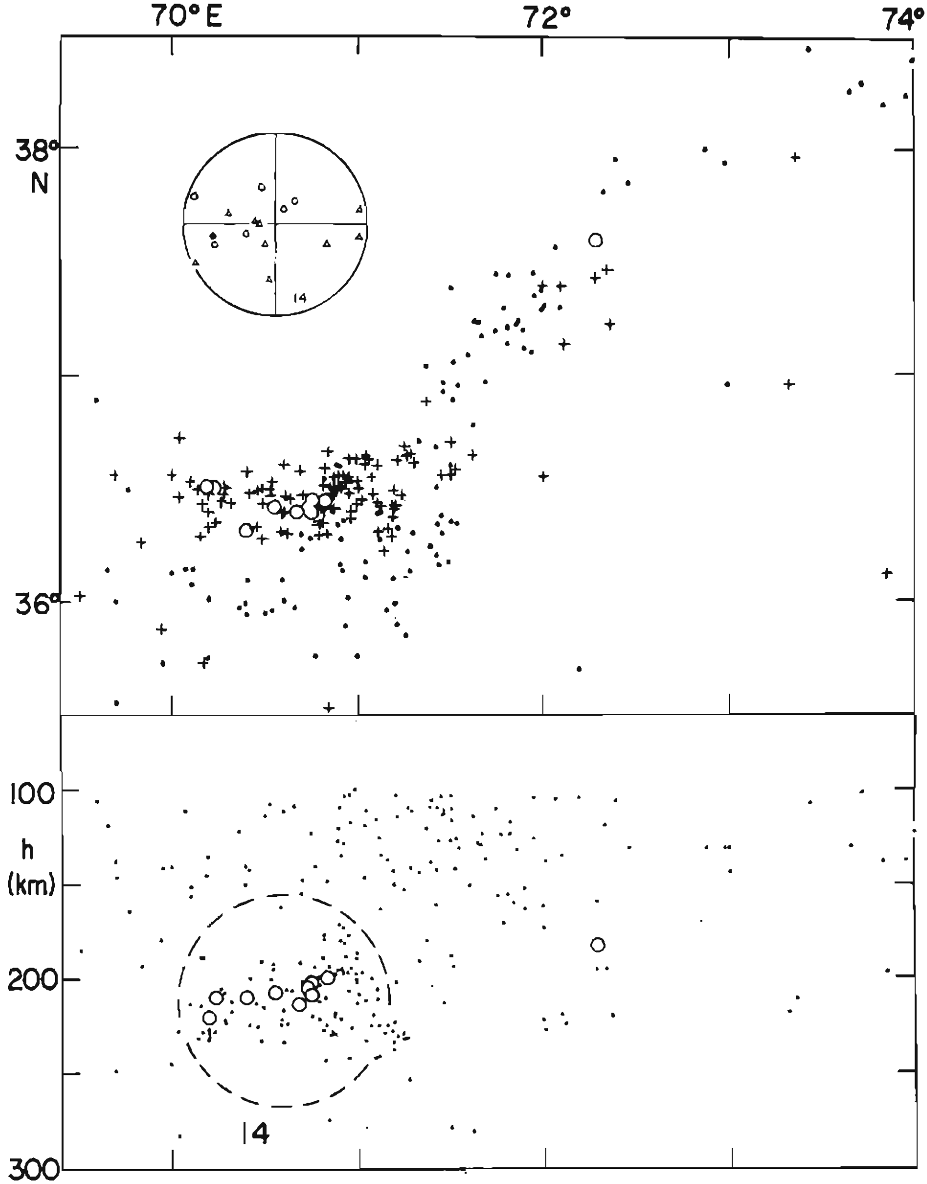

Fig. 26. Hindu-Kush region.
· ; h = 100-179 km,
+ ; h = 180-300 km,
○ ; Multiplets of $T \leq 5000$ min and $L \leq 20$ km.
In the directional distribution,
○, △ ; $T \leq 5000$ min and $L \leq 20$ km,
● ; T = 357 min and L = 20.3 km.

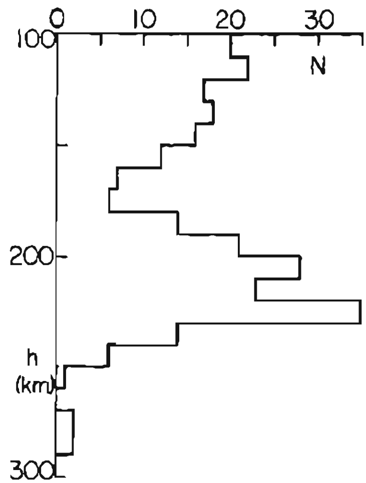

Fig. 27. Vertical distribution of earthquakes in the Hindu-Kush region.

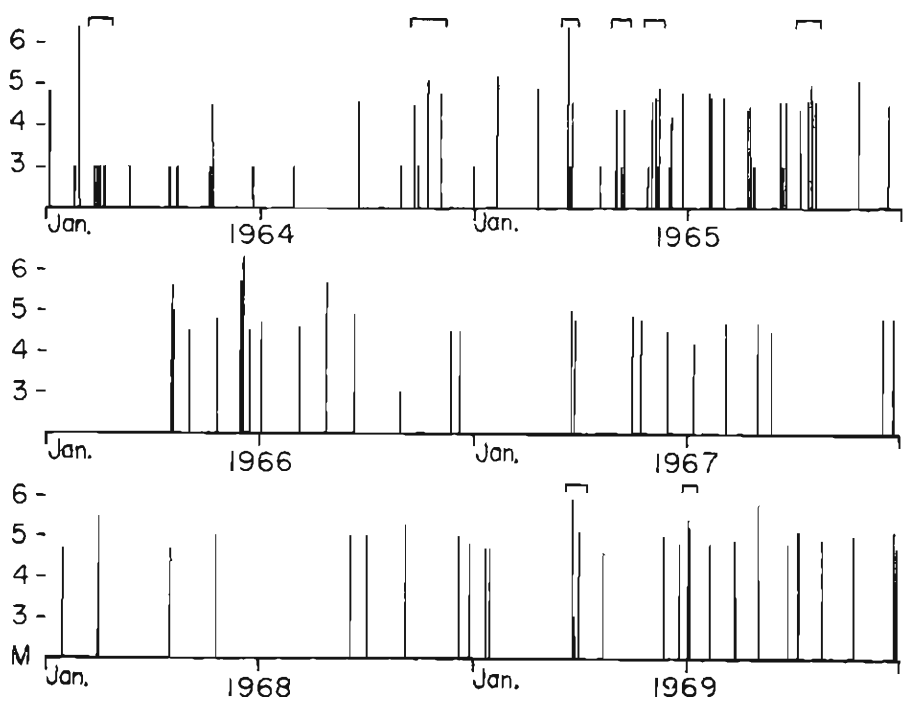

Fig. 28. Time sequence in the Hindu-Kush (14) area.

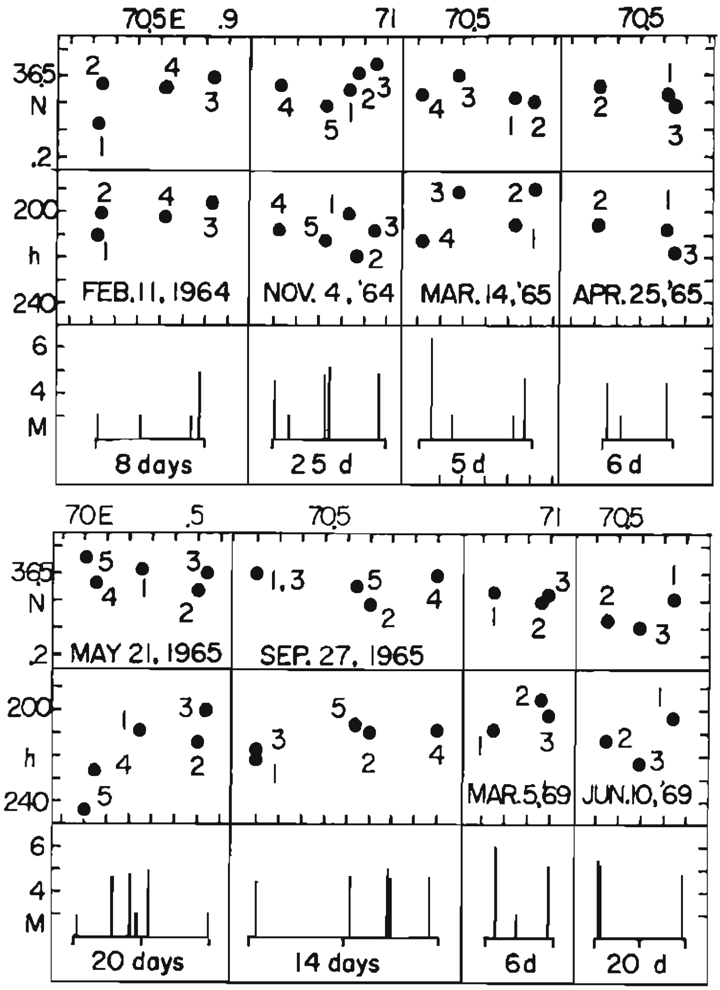

Fig. 29. Multiplets in the Hindu-Kush area.

5. Discussions and Conclusions

In the foregoing section various characteristics of the multiplets in each region are described. The following characteristics then, can generally be found in multiplets.

a). Multiplets defined in the form of short time intervals within about 10 days and space intervals of about 30 km between successive shocks, are rarely observed in Central America, Kuril-Japan, the Izu-Marianas or the Ryukyu regions.

b). On the contrary, they are frequently observed in the intermediate zones of the South Sandwich Islands, Colombia, Celebes Island, the Banda Sea, New Guinea, the New Hebrides Islands and the Hindu-Kush, and in the deep zones of South America, the Java-Banda Sea, the Santa Cruz Islands and the Fiji Islands. It is concluded that multiplets most frequently occur in the bent edges or the contortions of

the descending lithospheric plates which have been investigated by Isacks and Molnar (1971).[41]
c). Hypocenters of each multiplet distribute in the direction parallel to a proper plane and to the area independently of the number of shocks in a multiplet and the time and space intervals of their foci. These directions make an angle with the seismic plane in several areas.
d). Hypocenters of each multiplet which consists of more than three shocks distribute on a long and slender plane. The largest shock in the multiplet occurs at the end of the plane. In a few cases the hypocenters distribute on a plane at the first sequence and lastly distribute on another plane which is perpendicular to the first. This implies that a conjugate set of fault planes are generated by the occurrence of the multiplet.
e). From the time sequences of multiplets it is concluded that in some cases the largest shock occurs at the beginning of the series, almost all of which are the O–B_0, B_1, B_2 and O–C types according to the classification of earthquake sequences by Utsu (1970).[42]

As is analogized from the mechanism of the occurrence of shallow earthquakes, it is thought that the regional distribution of multiplets described above in a) and b) indicates regional differences in the physical properties of the structure and the stress field in the upper mantle. Particularly, the abundance of multiplets in regions where the seismic planes show complex features which are related to the complex pattern of the stress field.

The characteristics of the distribution of shocks described in c) and d) are the influence of the change if the stress field caused by the occurrence of fault planes.

The predominant type for time sequences of intermediate and deep multiplets is different from that of shallow earthquakes which occur with a greater number of after-shocks or in swarms. This difference may be caused by the difference in the physical conditions between crust and the upper mantle.

Accepting that the characteristic distribution of hypocenters in a multiplet indicates the local concentration of stresses along the edge of a main fault plane, or the pauses during the course of fault propagation, it is reasonable to conclude that the distribution of shocks is closely related to the principal axes of the earthquake generating stresses in the concerned area.

To confirm this the directional distributions of subsequent foci seen from the first are compared with the smoothed radiation patterns of the initial P waves in the corresponding area obtained by Oike (1971).[43] The relations are shown in Fig. 30 by superposing them on the hemi-sphere. In the 3–d and 9 areas, directions of subsequent foci do not distribute around the maximum and minimum values of the normalized parameter k which coincide with the directions of the axes of the maximum pressure and tension, respectively. In the 14 area in the Hindu-Kush region, they distribute only in the negative range of k.

Models are proposed in Fig. 31 to explain two types of patterns in Fig. 30. Open

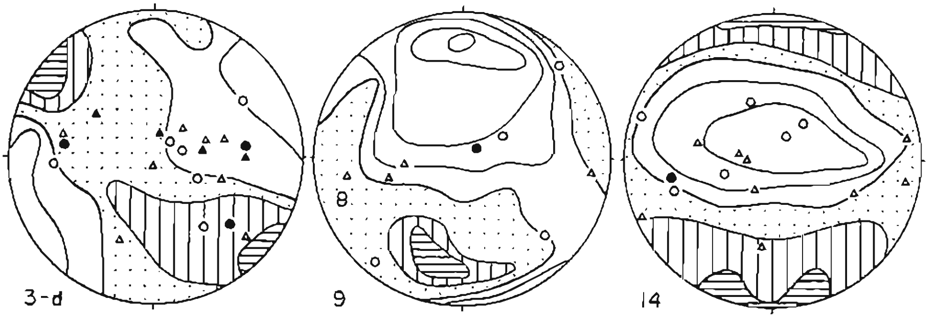

Fig. 30. Relation between the directional distribution of the subsequent foci seen from the first in the multiplets and the smoothed radiation pattern of P waves in the same area. The lines of equal values of normalized parameter k are drawn by the intervals of 0.2, and ranges with the patterns are positive.

and closed circles in Fig. 31 indicate the axes of the maximum pressure and tension. In the case of (a), principal stresses have the relation of $\sigma_1 > \sigma_2 > \sigma_3$ and in (b) $\sigma_1 \approx \sigma_2 > \sigma_3$ according to Balakina (1962)[44] and Shiono (1970).[45] In these two cases nodal planes of the fault plane solutions distribute differently as shown by the hatched range in figures. As the subsequent foci are thought to distribute on the fault plane of the first shocks, model (a) corresponds with patterns of the 3–d and 9 areas and (b) corresponds with 14 areas in Fig. 30, respectively.

Comparing the total number of intermediate and deep earthquakes observed throughout the world, multiplets account for only a small percent. In contrast with large shallow earthquakes with numerous after-shock, large intermediate and deep earthquakes are seldom accompanied with fore-and after-shocks so far observed. The concentration of stresses in the upper mantle seems to be released by the isolated occurrence of the slip dislocation along a single fault plane and the stress field around the fault is smoothed and stabilized by it. It is probable that multiplets occur when there are any unusual conditions in the focal regions, for example the heterogeneous distribution of stresses and materials.

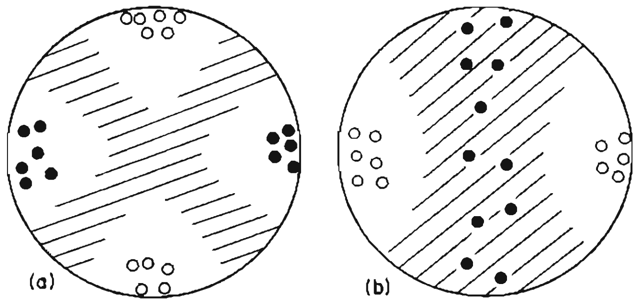

Fig. 31. Models to explain the results in Fig. 30. Open circles and closed circles indicate the axes of maximum pressure and tension, respectively. Nodal planes distribute in the hatched range.

The relation between the properties of multiplets and focal mechanism of individual earthquakes must be investigated by determining the slip planes of main shocks from the analysis of wave forms as applied for example by Fukao (1970)[46] and Mikumo (1971).[47] Such detailed analyses of individual multiplets are left for future studies.

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References

1) Mogi, K.: Earthquakes and Fractures, Tectonophysics, Vol. 5, 1967, pp. 35–55.
2) Utsu, T.: Some Problems of the Distribution of Earthquakes in Time (Part 3), Geophys. Bull. Hokkaido Univ., Vol. 23, 1970, pp. 49–71.
3) Utsu, T.: Aftershocks and Earthquake Statistics (I)—Some Parameters Which Characterize an Aftershock Sequence and Their Interrelations—, J. Faculty of Science, Hokkaido Univ., Series VII (Geophys.), Vol. 3, 1969, pp. 129–195.
4) Utsu, T.: Aftershocks and Earthquake Statistics (II)—Further Investigation of Aftershocks and Other Earthquake Sequences Based on a New Classification of Earthquake Sequences—, J. Faculty of Science, Hokkaido Univ., Series VII (Geophys.), Vol. 3, 1970, pp 197–266.
5) Oike, K.: The Time Variation of the Focal Mechanism and the Activity of Earthquake Swarms, Bull. Disaster Prevention Res. Inst., Kyoto Univ., Vol. 19, Part 4, 1970, pp. 21–35.
6) Yamakawa, N.: Foreshocks, Aftershocks and Earthquake Swarms (I), A Definition of Foreshocks, Aftershocks and Earthquake Swarms and Its Application to Seismicity, Papers Met. Geophys., Vol. 17, 1966, pp. 157–189.
7) Yamakawa, N.: Foreshocks, Aftershocks and Earthquake Swarms (II), Areal Characteristics of Abnormal Seismic Activities, Papers Met. Geophys., Vol. 18, 1967, pp. 15–26.
8) Yamakawa, N.: Foreshocks and Aftershocks and Earthquake Swarms (III), Detailed Areal Characteristics of Aftershock Activities, Papers Met. Geophys., Vol. 18, 1967, pp. 77–88.
9) Yamakawa, N.: Foreshocks, Aftershocks and Earthquake Swarms (IV), Frequency Decrease of Aftershock Activity in Its Initial and Later Stages, Papers Met. Geophys., Vol. 19, 1968, pp. 109–119.
10) Yamakawa, N.: Foreshocks, Aftershocks and Earthquake Swarms (V), Distribution of Time Intervals Between Consecutive Shocks in the Initial and Later Stages of Afterschok Activity, Papers Met. Geophys., Vol. 19, 1968, pp. 437–445.
11) Mogi, K.: Development of Aftershock Areas of Great Earthquakes, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 46, 1968, pp. 175–203.
12) Mogi, K.: Some Discussion on Aftershocks, Foreshocks and Earthquake Swarms—The Fracture of a Semi-Infinite Body Caused by an Inner Stress Origin and Its Relation to Earthquake Phenomena (Third Paper), Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 41, 1963, pp. 615–658.
13) Utsu, T.: Time and Space Distribution of Deep Earthquakes in Japan, J. Faculty of Science, Hokkaido Univ., Series VII (Geophys.), Vol. 3, 1969, pp. 117–128.
14) Isacks, B., L.R. Sykes and J. Oliver: Spatial and Temporal Clustering of Deep and Shallow Earthquakes in the Fiji-Tonga-Kermadec Region, Bull. Seism. Soc. Amer., Vol. 57, 1967, pp. 935–958.
15) Santô, T.: Characteristics of Seismicity in South America, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 47, 1969, pp. 635–672.
16) Santô, T.: Regional Study of the Characteristic Seismicity of the World. Part II. From Burma down to Java, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 47, 1969, pp. 1049–1061.

17) Santô, T.: Regional Study of the Characteristic Seismicity of the World. Part III. New Hebrides Islands Region, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 48, 1970, pp. 1–18.
18) Santô, T.: Regional Study of the Characteristic Seismicity of the World. Part IV. New Britain Island Region, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 48, 1970, pp. 127–143.
19) loc. cit. 4).
20) Oike, K.: The Deep Earthquake of June 22, 1966 in Banda Sea: A Multiple Shock, Bull. Disaster Prevention Res. Inst., Kyoto Univ., Vol. 19, 1969, pp. 55–65.
21) Fukao, Y.: Focal Process of A large Deep-Focus Earthquake as Inferred from Long-Period P Waves—The Western Brazil Earthquake of 1963—, in press.
22) Oike K.: On the Nature of the Occurrence of Intermediate and Deep Earthquakes. 1. The World Wide Distribution of the Earthquake Generating Stress, Bull. Disaster Prevention Res. Inst., Kyoto Univ., Vol. 20, Part 3, 1971, pp. 145–182.
23) Vere-Jones, D., S. Turnovsky and G.A. Eiby: A Statistical Survey of Earthquakes in the Main Seismic Region of New Zealand; Part 1. Time Trends in the Pattern of Recorded Activity, N.Z.J. Geol. Geophys., Vol. 7, 1964, pp. 722–744.
24) Vere-Jones, D. and R.B. Davies: A Statistical Survey of Earthquakes in the Main Seismic Region of New Zealand; Part 2. Time Series Analysis, N.Z.J. Geol. Geophys., Vol. 9, 1966, pp. 251–284.
25) loc. cit. 14).
26) Utsu, T.: Some Problems of the Distribution of Earthquakes in Time (Part 1), Geophys. Bull., Hokkaido Univ., Vol. 22, 1969, pp. 73–93.
27) Tomoda, Y.: On the Space Distribution Law of Earthquake Epicenter, Zisin, Vol. 5, 1952, pp. 1–6.
28) loc. cit. 13).
29) Abe, K.: Focal Process of the South Sanswich Islands Earthquake of May 26, 1964, in press.
30) Chandra, U.: The Peru-Bolivia Border Earthquake of August 15, 1963, Bull. Seism. Soc. Amer., Vol. 60, 1970, pp. 639–646.
31) loc. cit. 21).
32) loc. cit. 15).
33) loc. cit. 22).
34) loc. cit. 13).
35) loc. cit. 16).
36) loc. cit. 20).
37) loc. cit. 17).
38) loc. cit. 14).
39) Isacks, B., L.R. Sykes and J. Oliver: Focal Mechanisms of Deep and Shallow Earthquakes in the Tonga-Kermadec Region and the Tectonics of Island Arcs, Geol. Soc. Amer. Bull., Vol. 80, 1969. pp. 1443–1470.
40) loc. cit. 22).
41) Isacks, B. and P. Molnar: Distribution of Stresses in the Descending Lithosphere from a Gloval Survey of Focal Mechanism Solutions of Mantle Earthquakes, Rev. Geophys., Vol. 9, 1971, pp. 103–174.
42) loc. cit. 4).
43) loc. cit. 22).
44) Balakina, L.F.: General Regularities in the Directions of the Principal Stresses Effective in the Earthquake Foci of the Seismic Belt on the Pacific Ocean, Izv., Geophys. Ser. (Engl. Transl.), 1962, pp. 918–926.
45) Shiono, K.: Focal Mechanism of Local Earthquakes in Wakayama Region (Part 2), Zisin, Vol. 23, 1970, pp. 253–263.
46) Fukao, Y.: Focal Process of a Deep-Focus Earthquake As Deduced from Long-Period P and S Waves, Bull. Earthq. Res. Inst., Tokyo Univ., Vol. 48, 1970, pp. 707–727.
47) Mikumo, T.: Source Process of Intermediate-Depth Earthquakes As Inferred from Long-Period P and S Wave Forms, J. Phys. Earth, Vol. 19, 1971, pp. 1–19.